



## Basic Science

## Determining 3D Kinematics of the Hip Using Video Fluoroscopy: Guidelines for Balancing Radiation Dose and Registration Accuracy



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## ABSTRACT

**Background:** Video fluoroscopy is a technique currently used to retrieve the in vivo three-dimensional kinematics of human joints during activities of daily living. Minimization of the radiation dose absorbed by the subject during the measurement is a priority and has not been thoroughly addressed so far. This issue is critical for the motion analysis of the hip joint, because of the proximity of the gonads. The aims of this study were to determine the x-ray voltage and the irradiation angle that minimize the effective dose and to achieve the best compromise between delivered dose and accuracy in motion retrieval.

**Methods:** Effective dose for a fluoroscopic study of the hip was estimated by means of Monte Carlo simulations and dosimetry measurements. Accuracy in pose retrieval for the different viewing angles was evaluated by registration of simulated radiographs of a hip prosthesis during a prescribed virtual motion.

**Results:** Absorbed dose can be minimized to about one-sixth of the maximum estimated values by irradiating at the optimal angle of 45° from the posterior side and by operating at 80 kV. At this angle, accuracy in retrieval of internal-external rotation is poorer compared with the other viewing angles.

**Conclusion:** The irradiation angle that minimizes the delivered dose does not necessarily correspond to the optimal angle for the accuracy in pose retrieval, for all rotations. For some applications, single-plane fluoroscopy may be a valid lower dose alternative to the dual-plane methods, despite their better accuracy.

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Video fluoroscopy is an accurate and minimally-invasive technique currently used for the analysis of in vivo joint kinematics. A sequence of fluoroscopic images of the joint of interest is collected while the subject performs a specific motion task. For each frame, the three-dimensional (3D) pose of the joint is retrieved by matching a 3D model of each segment to its two-dimensional (2D) projection in the corresponding image, that is, 2D-to-3D registration [1]. The movement is finally reconstructed from the sequence of registered poses. Fluoroscopy of the hip has been performed to analyze gait on a treadmill [2–5], stair climbing [6], and isolated abduction [2,7].

As with conventional radiography, fluoroscopy imaging involves exposure of the subject to ionizing radiation. According to the As

Low As Reasonably Achievable radiation safety principle, all reasonable methods should be used to minimize radiation dose. In video fluoroscopy, a trade-off exists between image quality and radiation exposure. Acquisition of image data at high frame rates for dynamic events requires greater x-ray exposure to increase brightness and obtain the image quality required to achieve sufficient registration accuracy [8]. Furthermore, x-ray imaging of the hip requires typically higher exposure compared with imaging other peripheral joints of the body, because the image contrast is limited by a greater amount of surrounding tissue. However, higher x-ray exposure is associated with increased dose absorbed by the subject [9]. This issue is particularly critical for the hip because of the proximity of the gonads—the risk of biological damage to the gonads attributed by the International Commission on Radiation Protection (ICRP) is 2 times the risk assigned to bladder, liver, and thyroid glands and 8 times the risk assigned to the bone surface, skin, and brain [10]. The radiation dose is doubled when dual-plane fluoroscopy is used to acquire a pair of simultaneous images [4,5] as a means to improve the accuracy in pose retrieval.

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Many in vivo fluoroscopic studies of the hip lack information concerning radiation exposure [2,6,7,11–14] or report only the fluoroscopic settings without dose estimations [4]. The studies that provided values for the absorbed dose [5,15–17] did not explain the method used for their estimations and did not characterize the dependency of the dose on the imaging parameters. Effective dose can be estimated from the product between the kerma-area product, usually provided by the fluoroscope, and a reference dose conversion coefficient (DCC) [18] that is specific for the diagnostic procedure and the irradiated organs [19]. However, the values for the kerma-area product are not validated with in-situ dosimetry measurements and the reference values for the DCC, although derived from Monte-Carlo simulations using anthropomorphic digital phantoms, are not specific for the subject (gender, body mass index [BMI]), for the measurement geometry (distance and position of the patient with respect to the beam), and for the imaging settings (voltage, current, pulse width). For example, Le Heron [20] estimated that for the trunk region the DCC for the lateral and the posteroanterior (PA) radiographic projections are approximately half those corresponding to anteroposterior (AP) projection.

Considering the safety implications of radiation exposure, and the discrepancies in reported radiation dose for current fluoroscopy studies, the first aim of this study was to accurately estimate the radiation dose during hip imaging and to determine the imaging parameters that minimize the dose while providing acceptable image quality. The variable parameters investigated for this analysis were the x-ray voltage and the irradiation angle with respect to the pelvis.

For single-plane use, the fluoroscope must be positioned carefully to obtain sufficient bony details from optimized viewing angles, while minimizing occlusion of surrounding tissues and out-of-plane movement for the analyzed activity [15]. Hence, registration accuracy is influenced by imaging angle and must be considered together with dose minimization. The second aim of this study was to quantitatively investigate the dependence of the registration accuracy on the viewing angle of single-plane fluoroscopy, for a specific motion task.

## Material and Methods

### Estimation of Dose

Effective dose (Sv) for a fluoroscopic study of the hip was estimated by means of Monte Carlo simulations and dosimetry measurements with an Alderson phantom. Estimations were obtained for 2 different x-ray voltages, 80 kV and 100 kV, and 5 different irradiation angles described in Figure 1. The values for the x-ray voltages were comparable with those used in previous x-ray studies of the hip [4,5,15–17,21]. On the clinical fluoroscope incorporated in the imaging system, tube current is not independently adjustable. The tube current was automatically set by the fluoroscope to 12 mA for both voltages.

Monte Carlo methods with the Geant4 library [22] were used to simulate the x-ray irradiation of a 3D human model with 73 different organs and a voxel size of  $2 \times 2 \times 2 \text{ mm}^3$ . Material properties of each organ were assigned according to the tissue composition provided by the ICRP [23]. The x-ray beam used in the simulations was modeled according to the specifications of the used fluoroscope (BV Pulsera, Philips Medical Systems, Switzerland). The beam aperture was  $17^\circ$ . The output of the simulation was the average absorbed dose  $H_T$  (Gy) for each organ, a deterministic quantity accounting for the amount of deposited energy. The simulated effective dose  $E_S$  was computed as the weighted sum of the absorbed doses over all organs of the body (Equation 1). The organ-specific weighting factors  $W_T$  account for

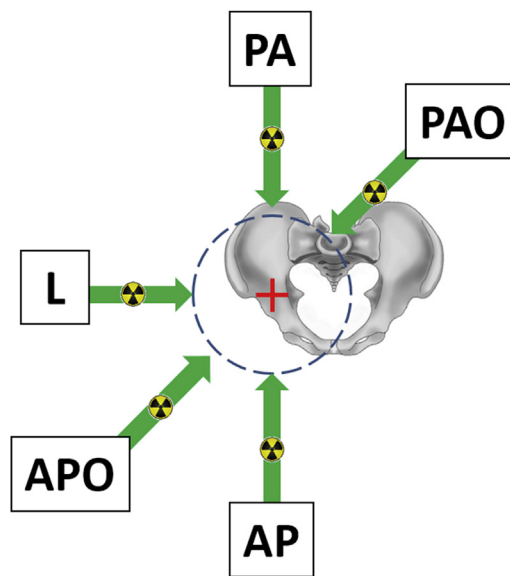


Fig. 1. Top view of a pelvis with the simulated irradiation angles. AP, anteroposterior; L, lateral; PA, posteroanterior; APO, anteroposterior oblique; PAO, posteroanterior oblique.

the stochastic biological risk associated with radiation exposure and are defined by the ICRP.

$$E_S = \sum W_T H_T \quad (1)$$

Simulations at different irradiation angles (Fig. 1) and different x-ray voltages were performed. With experimental setups analogous to each simulation, the entrance dose to an Alderson phantom placed at a distance of 70 cm from the x-ray source was measured while operating the fluoroscope at a frame rate of 25 Hz and pulse width of 8 ms (Fig. 2). For each case, the dose-area product ( $\text{Gy} \cdot \text{m}^2$ ) was measured with a dosimeter. The simulated effective dose was then scaled with the ratio of the measured dose-area product  $D_M R_M^2$  to the simulated dose-area product  $D_S R_S^2$  (Equation 2) to retrieve the estimated effective dose  $E$  for each measurement setting.

$$E = E_S \frac{D_M R_M^2}{D_S R_S^2} \quad (2)$$

Because of the different position between the female and the male gonads, simulations for both a female subject (58 kg, 1.66 m, BMI 21  $\text{kg}/\text{m}^2$ ) and a male subject (80 kg, 1.73 m, BMI 27  $\text{kg}/\text{m}^2$ ) were carried out.

In addition, simulations for a shielded male patient were performed to quantitatively evaluate the benefit brought by gonad protection. Shielding was modeled with a 2–4 mm thick lead sheet placed in front of the testes.

### Estimation of Registration Accuracy

Pose accuracy for the different viewing angles was evaluated by registration of simulated radiographs of a hip prosthesis during a prescribed virtual motion. Because accuracy is expected to depend on the specific motion task, level walking and sitting on a chair were chosen as activities covering typical range of motion of the hip joint. For each of these, the following procedure was carried out:

1. Realistic motion of the hip was retrieved from the public database [www.OrthoLoad.com](http://www.OrthoLoad.com) [24] and applied to 3D models of the cup and the femoral stem of the prosthesis;

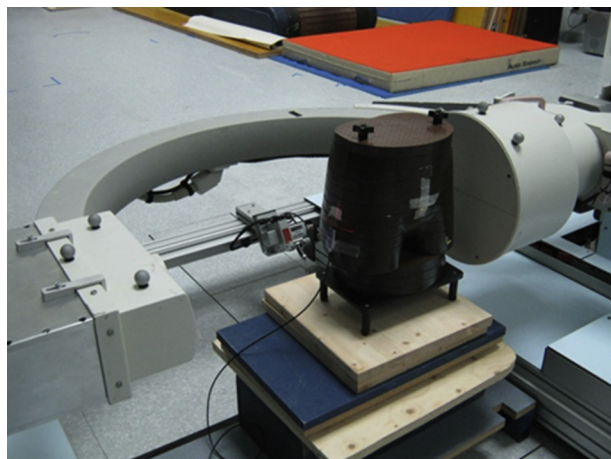


Fig. 2. Alderson phantom irradiated with fluoroscope at the L view.

2. A simulated fluoroscopic image was generated by a perspective projection model, and for each viewing angle, a sequence of simulated radiographs of the hip prosthesis during motion was analyzed (Fig. 3);
3. Implant pose at each motion step was determined from the images by means of 2D-3D registration;
4. Accuracy was evaluated by calculating the registration error, as the difference between the registered pose and the prescribed pose over the whole motion sequence.

2D-3D registration was performed with the graphical user interface provided by the open source software Joint Track [18,25]. Manual matching was performed to exclude the influence of a specific automatic registration algorithm. In addition, a reproducibility study of the results over multiple manual registrations was carried out to evaluate the interuser variability. One single-position was chosen and registered 10 times per viewing angle.

The coordinate systems of the acetabular cup and the femoral components were defined according to the standard recommendation of the International Society of Biomechanics [26]. For each motion step, the implant pose relative to the reference standing position was described as a sequence of consecutive flexion, abduction, and internal rotation of the femoral stem with respect to the cup followed by translation. Registration error was computed for each of the 3 rotational and the 3 translational components describing the implant pose. However, because of the symmetry of the cup around its geometrical axis, the rotational position for the cup cannot be fully determined. Therefore, the registration errors for rotation were evaluated for the femoral component only.

Accuracy for each viewing angle was evaluated by computation of the root mean square (RMS) value of the registration error over a whole motion sequence. Statistical differences between the registration errors for each angle were evaluated with a one-way analysis of variance (significance level of 0.05) followed by a multi-comparison test with Tukey correction.

**Results**

*Estimation of the Dose*

The dose is generally lower for lower voltages and for irradiation from the back (Fig. 4). Values estimated for 100 kV were higher than those predicted for 80 kV, by a factor of 2.0-2.2. The highest doses were found for AP and anteroposterior oblique irradiations (Fig. 1),

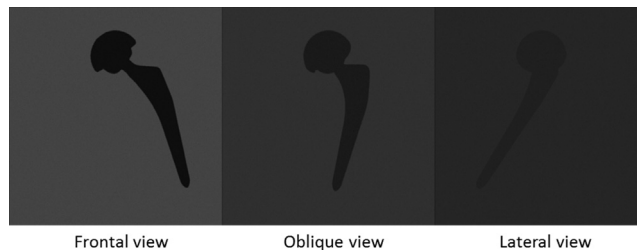


Fig. 3. Simulated fluoroscopic images of a prosthetic hip implant at different viewing angles. For each image, contrast between the implant and background and representative Gaussian noise have been reproduced from measurements on real fluoroscopic images collected at these angles. The image contrast gradually decreases from the frontal view to the lateral view because of the different amounts of pelvic bone and soft tissue traversed by the x-ray beam.

where the gonads are more exposed to the beam and less shielded by the surrounding tissues. Effective dose can be reduced to about one-sixth of the highest value by collecting x-ray images with a voltage of 80 kV and a 45° posterior angle (posteroanterior oblique [PAO]).

The values estimated for a female phantom were higher than those for a male phantom by a factor ranging from 1.3-1.9. The main contribution to the higher effective dose comes from the ovaries—these are more directly exposed than the testes, because they are located at the same height as the hip joint.

Simulations for a male patient showed that gonad protection with the metal shielding modeled in this study does not significantly reduce the dose. Only the effective dose for AP irradiation was reduced by 10% relative to the unshielded case.

*Estimation of the Registration Accuracy*

RMS of the registration error over a whole motion sequence at the different viewing angles is reported in Table 1, for each of the three rotational components describing the pose of the femoral component of the hip prosthesis.

Generally, lower accuracy was observed for the rotations involving larger out-of-plane movement. For gait, flexion was registered from the lateral view with the smallest RMS error of 0.17°, whereas RMS errors for the PA and the PAO views were 1.34° and 1.41° RMS, respectively. Abduction was registered with the smallest RMS error of 0.16° from the PA view, whereas RMS errors for the PAO and the L views were 1.26° and 2.89°, respectively. For sitting down on a chair, abduction was retrieved with the smallest

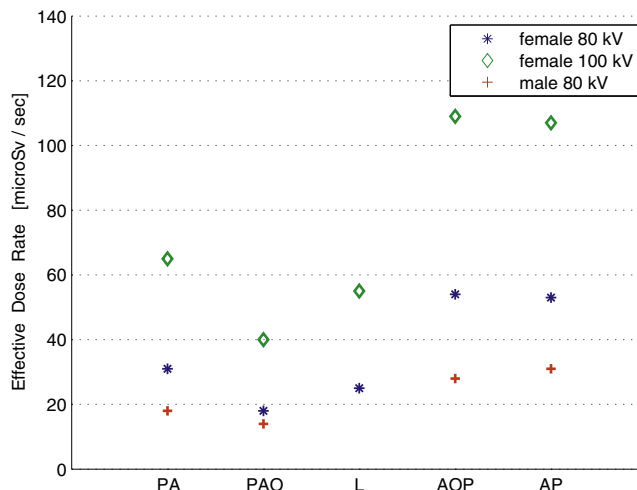


Fig. 4. Effective dose rates (μSv/s) estimated for a female and a male subject at different irradiation angles (as described in Fig. 1) and voltages.

RMS error of 0.2° from a PA view, whereas poorer performance was seen from the other angles. However, no substantial differences in accuracy were found for the flexion component, because RMS errors for all angles were around 0.5°. For internal rotation, the oblique view (PAO) was found to provide the worst accuracy for both gait and sitting down on a chair, showing a RMS error of 2° and 1.7°, respectively; on the contrary, subdegree errors were observed from the PA and the L views.

Results from the reproducibility study (Fig. 5) over multiple registrations ( $n = 10$ ) showed statistically significant differences in registration error for different irradiation angles. The observed trends in pose accuracy over the full motion cycle were therefore confirmed also for reproducibility—the frontal view (PA or AP) provides statistically better results for abduction ( $P < .01$ ), the lateral view provides statistically better results for flexion ( $P < .01$ ), whereas the oblique view (PAO or POA) gives the worst results for internal rotation ( $P < .01$ ).

## Discussion

This study provides a quantitative comparison of the dose absorbed by a subject over different irradiation angles and x-ray voltages during video fluoroscopy of the hip. Imaging settings that minimize the dose were identified. The registration accuracy for the femoral component of a hip prosthesis during two dynamic activities was evaluated for the optimal irradiation angle and compared with the accuracy observed for the same motions at the other angles.

Radiation dose delivered to the patient during pulsed fluoroscopic imaging of the hip joint at a frame rate of 25 Hz, pulse width of 8 ms was estimated to range from 18–109  $\mu\text{Sv}$  per second of measurement, depending on the irradiation angle. Thus, for a fluoroscopic measurement of 20 seconds, estimated effective dose ranges from a minimum of 0.36 to a maximum of 2.18 mSv. The maximum estimated dose corresponds to approximately 3 times the radiation exposure for radiography of the hip, to 0.36 times either the exposure for a computed tomography scan of the pelvis or for an upper gastrointestinal series [27], and to 10% of the yearly occupational exposure limit. Especially for research in movement analysis, larger measurement times and consequently higher dose might be needed to analyze a broader spectrum of motion activities.

The maximum values of absorbed dose were observed for a voltage of 100 kV and irradiation angles with the x-ray source on the anterior side. These suboptimal angles, however, have been adopted so far in many dual-plane fluoroscopic studies of the hip [5,6,16,21]. The present study shows that the dose can be reduced by up to 3 times simply if the positions of the x-ray source and the detector are reversed so that irradiation comes from a posterior direction. Because no substantial changes of the image quality are expected from the positional switch, the dose reduction comes at no expense for registration accuracy. Lateral imaging is not recommended, because of poor contrast at acceptable fluoroscope settings.

Dose can be minimized to about one-sixth of the maximum values by irradiating at the optimal angle of 45° from the posterior side and by operating at 80 kV. Most fluoroscopy studies were performed at a voltage around 80 kV [4,5,15–17]. However, fluoroscopic measurements of the Alderson phantom showed that image quality is better at 100 kV than at 80 kV. Nevertheless, the estimated dose at the optimal angle and voltage of 100 kV was one-third of the maximum value.

2D-3D registration accuracy for total hip arthroplasty (THA) with single-plane fluoroscopy estimated in the present study can be directly compared with values found in literature for the AP view

**Table 1**

RMS Errors for the Pose of a Femoral Component of a Hip Prosthesis During Simulated Gait (A) and Sitting Down on a Chair (B) at Different Irradiation Angles.

	PA = AP, °	APO = APO, °	L, °
Gait (A)			
Flexion	1.35	1.41	0.17
Abduction	0.17	1.26	2.89
Internal rotation	0.81	2.00	0.69
Sitting down (B)			
Flexion	0.67	0.58	0.44
Abduction	0.21	0.79	2.04
Internal rotation	0.66	1.75	1.03

The simulated images for the AP view are equivalent (but mirrored) to the images from the PA view, and thus the corresponding registration accuracies are the same. An irradiation angle of 45° was identified in the first part of the study as optimal for minimizing dose.

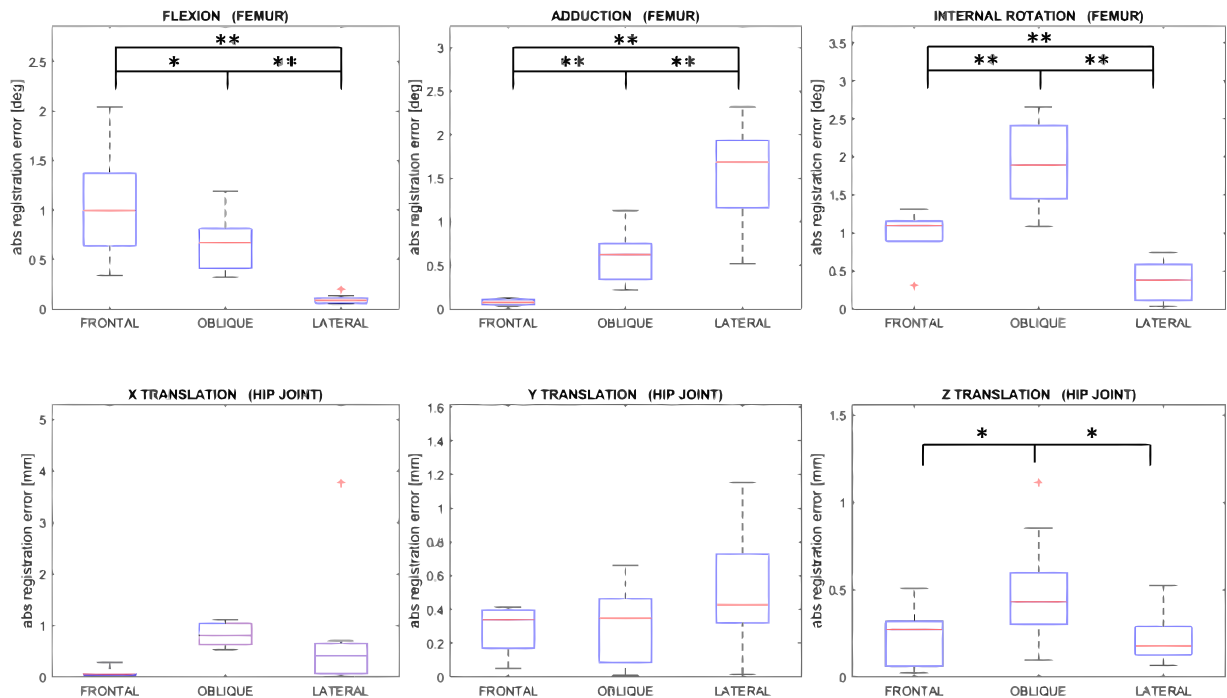
AP, anteroposterior; PA, posteroanterior; RMS, root mean square; APO, anteroposterior oblique.

only. Rotational errors  $<0.75^\circ$  reported by in vitro studies [2,11] are comparable with the estimated errors for the in-plane rotations (RMS  $<0.44^\circ$ ), but much smaller than some of the observed out-of-plane errors. The error difference between in-plane and out-of-plane rotations observed in the present study for the level walking was also observed in a simulation study [14] similar to the present one (errors of 1.45°, 0.12°, 0.61° for flexion, abduction, and internal rotation, respectively).

To our knowledge, there are no research studies characterizing the registration accuracy of THA for single-plane fluoroscopy at different irradiation angles. Tersi et al [28] focused on the quantification of the registration accuracy for the natural knee joint with single-plane and dual-plane fluoroscopy and compared the performances between the two single-plane views of the dual setup. The two single-plane views corresponded approximately to an AP view and a PAO view, and the simulated motion was level walking. Although the joint of interest was not the prosthetic hip, similarities can be found with the results from the present study. First, larger errors and relatively large dispersion were observed for the out-of-plane rotations, comparable with the present analysis. The reproducibility study showed standard deviations of the RMS error for flexion from the AP view and for abduction from the L view as high as 0.57° (Fig. 5). Second, internal-external rotation was particularly critical from the oblique view (median error of 2.3° with dispersion of 5.1°). The present study confirmed that the oblique view provides the lowest accuracy for the internal rotation: RMS error was 2.00° for level walking and 1.75° for sitting down, corresponding to about one-fourth and to half of the range of motion, respectively. This may be due to the longitudinal symmetry of the femoral stem [21,28]. The oblique view aligns with the anteversion angle of the cup, resulting in major overlap of the femoral head and neck with the cup in the radiographic image, and consequently, in limited visibility of the useful contours of the femoral component.

The irradiation angle that minimizes the delivered dose does not necessarily correspond to the optimal angle for the accuracy in pose retrieval, for all rotations. In fact, the PAO irradiation angle provided the worst results for the internal-external rotation, for both activities. If subdegree accuracy for all rotations is needed with single-plane fluoroscopy, none of the angles is sufficient for gait and only the PA = AP angle is sufficient for sitting down. In a clinical environment, the trade-off between dose and accuracy can be a major constraint and the PAO view can represent a valid compromise, depending on the type of analysis and the needed accuracy.

The present study showed that single-plane fluoroscopy provides RMS rotational errors up to 2.9° (for abduction from the



**Fig. 5.** Reproducibility study of the relative registration accuracy at different viewing angles over multiple registration trials. One star corresponds to  $P < .05$ , 2 stars correspond to  $P < .01$ .

L view) and that registration accuracy is affected by the irradiation angle. On the contrary, dual-plane techniques were proved to be substantially more accurate; for THA kinematics, RMS rotational errors were less than  $0.74^\circ$  for the hip joint and less than  $0.65^\circ$  specifically for the femoral component [4], with no significant differences between in-plane and out-of-plane rotations; studies on the native hip joint proved accuracies (bias) better than  $0.69^\circ$  [15], precisions better than  $0.8^\circ$  [21], and bias and precision less than  $0.58^\circ$  and better than  $0.78^\circ$ , respectively [17]. In addition, the similarity of the results obtained from different bi-planar setups suggests that the registration accuracy of dual-plane techniques does not depend on the irradiation angles of the 2 fluoroscopic units and on the relative angle between them. However, other limitations compared with single-plane fluoroscopy exist besides the doubled radiation dose: the restricted field of view of dual setups limits measurements of hip motion when the hip moves in space, such as during a lunge or stair ascent [6,15,28]; furthermore, the bulky equipment may not be suited for movable fluoroscopy for the tracking of complex activities, as for some studies with single-plane fluoroscopy [29]. For the above reasons, single-plane techniques might represent a valid option at lower cost, image processing time and substantially lower radiation dose, with prior optimization of the irradiation angle based on the achievable accuracy, the delivered dose, and the activity in analysis. For example, single-plane techniques might provide kinematics suited for general input to musculoskeletal modelling, whereas dual-plane techniques should be adopted for the more demanding analysis of micro-separation of hip implants.

Concerning the limitations in the estimations of the absorbed dose, the computed absolute values are specific to the measurement settings chosen in this study and may vary when the distance of the patient from the x-ray source, the size of the patient, the quality or the direction of the x-ray beam are modified. Tube current was automatically set to 12 mA by our clinical image intensifier. Dose estimates, however, can be linearly scaled for

different values of tube current. Concerning the registration accuracy, estimations were carried out for the pose of the femoral component only, rather than for the relative pose between the femoral component and cup. Therefore, absolute total errors may be underestimated, although errors are not necessarily additive and the observed trends should remain valid. Motion blur generated by the imaging of dynamic activities was not considered. However, the focus of this study was a comparative analysis of the performance of single-plane methods at different irradiation angles, rather than the absolute accuracies. The relative performances are expected to be independent of the motion blur, the type and geometry of the joint/implant.

## Conclusions

X-ray fluoroscopy has the potential to become a routine technique to analyze patient-specific joint motion. However, minimization of the dose absorbed by the patient is a primary, overarching issue to address. The presented results should raise awareness of varying radiation doses, based on viewing angles of the fluoroscope, and provide general guidelines for future fluoroscopy studies of the hip, in terms of patient safety and accuracy in pose retrieval.

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## References

- [1] Markelj P, Tomažević D, Likar B, Pernuš F. A review of 3D/2D registration methods for image-guided interventions. *Med Image Anal* 2012;16:642–61.
- [2] V Lombardi A, Mallory TH, Dennis DA, Komistek RD, Fada RA, Northcutt EJ. An in vivo determination of total hip arthroplasty pistoning during activity. *J Arthroplasty* 2000;15:702–9.

- [3] Glaser D, Dennis DA, Komistek RD, Miner TM. In vivo comparison of hip mechanics for minimally invasive versus traditional total hip arthroplasty. *Clin Biomech* 2008;23:127–34.
- [4] Tsai TY, Li JS, Wang S, Lin H, Malchau H, Li G, et al. A novel dual fluoroscopic imaging method for determination of THA kinematics: in-vitro and in-vivo study. *J Biomech* 2013;46:1300–4.
- [5] Tsai TY, Li JS, Wang S, Scarborough D, Kwon YM. In-vivo 6 degrees-of-freedom kinematics of metal-on-polyethylene total hip arthroplasty during gait. *J Biomech* 2014;47:1572–6.
- [6] Dimitriou D, Tsai T-Y, Li J-S, Nam KW, Park KK, Kwon Y-M. In vivo kinematic evaluation of total hip arthroplasty during stair climbing. *J Orthop Res* 2015;33:1087–93.
- [7] Dennis DA, Komistek RD, Northcutt EJ, Ochoa JA, Ritchie A. 'In vivo' determination of hip joint separation and the forces generated due to impact loading conditions. *J Biomech* 2001;34:623–9.
- [8] Ackland DC, Keynejad F, Pandy MG. Future trends in the use of X-ray fluoroscopy for the measurement and modelling of joint motion. *Proc Inst Mech Eng H J Eng Med* 2011;225:1136–48.
- [9] Geise RA. Fluoroscopy: recording of fluoroscopic images and automatic exposure control. *Radiographics* 2001;21:227–36.
- [10] ICRP. ICRP 103: the 2007 recommendations of the international commission on radiological protection. *Ann ICRP* 2007;37:330.
- [11] Komistek RD, Dennis DA, Ochoa JA, Haas BD, Hammill C. In vivo comparison of hip separation after metal-on-metal or metal-on-polyethylene total hip arthroplasty. *J Bone Joint Surg Am* 2002;84-A:1836–41.
- [12] Tanino H, Ito H, Harman MK, Matsuno T, Hodge WA, Banks SA. An in vivo model for intraoperative assessment of impingement and dislocation in total hip arthroplasty. *J Arthroplasty* 2008;23:714–20.
- [13] Blumenfeld TJ, Glaser DA, Bargar WL, Langston GD, Mahfouz MR, Komistek RD. In vivo assessment of total hip femoral head separation from the acetabular cup during 4 common daily activities. *Orthopedics* 2011;34:127.
- [14] Koyanagi J, Sakai T, Yamazaki T, Watanabe T, Akiyama K, Sugano N, et al. In vivo kinematic analysis of squatting after total hip arthroplasty. *Clin Biomech* 2011;26:477–83.
- [15] Lin H, Wang S, Tsai TY, Li G, Kwon YM. In-vitro validation of a non-invasive dual fluoroscopic imaging technique for measurement of the hip kinematics. *Med Eng Phys* 2013;35:411–6.
- [16] Fiorentino NM, Kutschke MJ, Atkins PR, Foreman KB, Kapron AL, Anderson AE. Accuracy of functional and predictive methods to calculate the hip joint center in young non-pathologic asymptomatic adults with dual fluoroscopy as a reference standard. *Ann Biomed Eng* 2015:1–13.
- [17] Kapron AL, Aoki SK, Peters CL, Maas SA, Bey MJ, Zuel R, et al. Accuracy and feasibility of dual fluoroscopy and model-based tracking to quantify in vivo hip kinematics during clinical exams. *J Appl Biomech* 2014;30:461–70.
- [18] Thurston J. NCRP report no. 160: ionizing radiation exposure of the population of the United States. *Phys Med Biol* 2010;55:6327.
- [19] IAEA. Radiation Protection of Patients (RPOP) [Online]. [https://rpop.iaea.org/RPOP/RPoP/Content/InformationFor/HealthProfessionals/4\\_InterventionalRadiology/patient-staff-dose-fluoroscopy.htm#NCRP](https://rpop.iaea.org/RPOP/RPoP/Content/InformationFor/HealthProfessionals/4_InterventionalRadiology/patient-staff-dose-fluoroscopy.htm#NCRP) [accessed 20.03.16].
- [20] Le Heron JC. Estimation of effective dose to the patient during medical x-ray examinations from measurements of the dose-area product. *Phys Med Biol* 1992;37:2117–26.
- [21] Martin DE, Greco NJ, Klatt BA, Wright VJ, Anderst WJ, Tashman S. Model-based tracking of the hip: implications for novel analyses of hip pathology. *J Arthroplasty* 2011;26:88–97.
- [22] Agostinelli S, Allison J, Amako K. Geant4-a simulation toolkit. *Nucl Instr Methods Phys. Res. A* 2003;506:250–303.
- [23] ICRP. Adult reference computational phantoms ICRP. *Ann ICRP* 2009;110:162.
- [24] Bergmann G, Deuretzbacher G, Heller M, Graichen F, Rohlmann A, Strauss J, et al. Hip contact forces and gait patterns from routine activities. *J Biomech* 2001;34:859–71.
- [25] Mu S. JointTrack: an open-source, easily expandable program for skeletal kinematic measurement using model-image registration, MSc thesis, University of Florida. 2007; [http://ufdcimages.uflib.ufl.edu/UF/E0/02/17/84/00001/mu\\_s.pdf](http://ufdcimages.uflib.ufl.edu/UF/E0/02/17/84/00001/mu_s.pdf); <https://sourceforge.net/projects/jointtrack/> [accessed 05.06.17].
- [26] Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. *J Biomech* 2002;35:543–8.
- [27] Mettler FA, Huda W, Yoshizumi TT, Mahesh M. Effective doses in radiology and diagnostic nuclear medicine: a catalog. *Radiology* 2008;248:254–63.
- [28] Tersi L, Barré A, Fantozzi S, Stagni R. In vitro quantification of the performance of model-based mono-planar and bi-planar fluoroscopy for 3D joint kinematics estimation. *Med Biol Eng Comput* 2013;51:257–65.
- [29] Zihlmann MS, Gerber H, Stacoff A, Burckhardt K, Székely G, Stüssi E. Three-dimensional kinematics and kinetics of total knee arthroplasty during level walking using single plane video-fluoroscopy and force plates: a pilot study. *Gait Posture* 2006;24:475–81.